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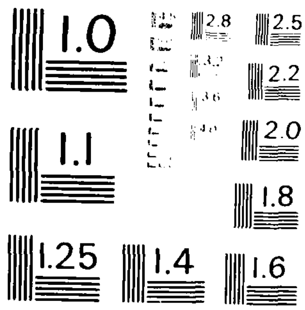
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ANALYSIS OF FERROGRAPHIC ENGINE WEAR DATA USING QUALITY CONTROL TECHNIQUES

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1. Background.

It is generally accepted that wear is the leading factor in engine and gear failure. There are many types of wear, some of which are: adhesion, abrasion, corrosion, erosion, fretting, cavitation, fatigue, melting, ablution and delamination. Each of these results in its characteristic form of wear particle, the identification of which is sometimes difficult. There are many methods for indentifying these particles and for monitoring their development over time. One such method is ferrography.

Ferrography is a technique developed by Seifert and Wescott for separating wear particles from the lubricant matrix and depositing these on a glass slide, arranged or sorted by particle size [4, 7]. This slide is then examined microscopically. An indirect measure of wear is obtained by measuring the amount of light which is transmitted through the glass slide, subject to the amount of particles which have been deposited. The transmittance is reported as the percentage of the area within the field of view which is covered by the deposited particles. Measurements are made in areas on the slide corresponding to the large particles and to the small particles. The two measurements are called by workers in the field, A_L and A_s respectively. The particles are deposited by dripping the engine or transmission oil onto an inclined glass slide which is immersed in a magnetic field. The larger particles are thus deposited first and the smallest particles, last. A good survey of this method is presented in [6].

2. Statement of Objective.

Our objective is to produce an easy to use method for improving the amount of information which can be obtained in Ferrography without an increase in time, effort and instrumentation. As things stand now, optical measurements are made from the ferrogram deposit and an index of wear severity, I_s is calculated using an arbitrary relationship

$$I_s = A_L^2 - A_s^2 \tag{1}$$

where A_L is percent area covered by particles at the entry deposit, (particles greater than 5 μm) and A_s is the percent area covered by particles at 50 mm from the exit of the Ferrogram, (particles ranging from 1 to 2 μm.) [6]. This index of severity, proposed by V. Wescott, is attractive because of its conciseness and the ease with which it is calculated. Since it contains only information obtained directly from the Ferrogram, this measure is apparently germane and relevant.

3. Brief Discussion of Current Methodology.

As a direct measure of wear, I_s is difficult to interpret. Let $\dot{I}_s$, $\dot{A}_s$ and $\dot{A}_L$ represent the time derivatives of I_s, A_s, and A_L. Notice that,

$$\frac{\partial I_s}{\partial A_s} = -2A_s < o, \text{ and } \quad \frac{\partial I_s}{\partial A_L} = 2A_L > o,$$

so that $\dot{I}_s = 2A_L\dot{A}_L - 2A_S\dot{A}_S$. Therefore, a net positive change in I_s can result from either an increase in A_L or a decrease in A_s. In general, simultaneous increases and/or decreases in A_L and A_s in differing amounts may result in either an increase or a decrease in I_s. In the following, we propose a change in this index which will produce a direct measure of the ferrogram information which is easy to compute and interpret.

A Ferrogram is an indirect measure of engine wear at a specific time so that, for practical purposes, it can be considered a monitoring process. The onset of failure is signalled by a fairly abrupt increase in A_L or A_s or both. Early failures are indicated by premature deviations from the normal values or trends in one of these parameters. It would be very useful to devise a scale for plotting Ferrogram values with automatic warning limits so that interpretation of individual cases could be reduced to a minimum. If this were accomplished with a preliminary sample or other past history (such as factory test data) to establish benchmarks, we will have described a quality control monitoring process.

Ferrogram measurements exhibit unpredictable variation which demands a statistical analysis for proper interpretation. Although the statistical distributions of A_L and A_s are somewhat normal in appearance [5], we suggest that several repeated measurements be taken of each value from each Ferrogram, yielding average $\bar{A}_L$ and $\bar{A}_s$, so that the assumption of normality may be justified by invoking the central limit theorom [3]. Since these measurements are taken from the same Ferrogram, there is the possibility of correlation between them. $\bar{A}_L$ and $\bar{A}_s$ are, however, related to the extreme values of the available measurements from the Ferrogram and are, therefore, related to the extreme order statistics. Since the extreme order statistics are asymptotically independent [2], $\bar{A}_L$ and $\bar{A}_s$ are assumed to be independent. We will, nevertheless, present a method which will allow for correlation between them.

4. Proposal for an Improved Method.

Let

x = sample average, $\bar{A}_L$, at time t

y = sample average, $\bar{A}_s$, at time t

$\mu_x(t)$ = expected value of $\bar{A}_L$ at time t

$\mu_y(t)$ = expected value of $\bar{A}_s$ at time t

σ_x^2 = variance of $\bar{A}_L$

σ_y^2 = variance of $\bar{A}_s$

ρ = correlation between $\bar{A}_L$ and $\bar{A}_s$

Under the assumptions stated previously, the joint statistical distribution of x and y is

$$f(x,y) = (2\pi\sigma_x\sigma_y\sqrt{1-\rho^2})^{-1} \exp\left[-g(x,y)/2(1-\rho^2)\right] \tag{2}$$

where

$$g(x,y) = \left(\frac{x-\mu_x}{\sigma_x}\right)^2 - 2\rho\left(\frac{x-\mu_x}{\sigma_x}\right)\left(\frac{y-\mu_y}{\sigma_y}\right) + \left(\frac{y-\mu_y}{\sigma_y}\right)^2 . \tag{3}$$

The appropriate regions for monitoring sample values (x,y) are the ellipses of equal probability density, for the probability

$$\alpha = \exp\left[-a^2/2\right], \tag{4}$$

$$\iint_A f(x,y)dxdy = 1 - \exp\left[-a^2/2\right], \tag{5}$$

where A is the region enclosed by the ellipse [1].

$$g(x,y) = a^2 \ (1-\rho^2) \quad . \tag{6}$$

In order to standardize the graphical representation of the sample values, it is recommended that the ellipses (6) be transformed to unit circles as follows. When x and y are independent the ellipse (6) becomes

$$\left(\frac{x-\mu_x}{\sigma_x}\right)^2 + \left(\frac{y-\mu_y}{\sigma_y}\right)^2 = a^2 \tag{7}$$

Let

$$ar = (x-\mu_x)/\sigma_x \quad \text{and} \quad as = (y-\mu_y)/\sigma_y \tag{8}$$

Then (7) becomes

$$r^2 + s^2 = 1 \ . \tag{9}$$

The new index of severity, J_s, is made by transforming the data thus:

$$u = \frac{x-\mu_x}{\sigma_x} \quad \text{and} \quad u = \frac{y-\mu_y}{\sigma_y} \tag{10}$$

Then,

$$J_s = u^2 + v^2 \tag{11}$$

is the proposed new index of severity. This value should be compared to an extreme upper tail percentage point of the central chi-square distribution with 2 degrees of freedom. For example, the probabilities =.01 and .005 correspond to the values 9.2 and 10.6, respectively. If there is correlation present these values are reduced, with the lower bounds 6.6 and 7.9 corresponding to perfect correlation. On the other hand, the onset of failure is marked by instability of the distribution of the particle sizes with A_L, A_s or both rapidly becoming very large, depending on the underlying cause of the failure. This implies that these measures change separately or independently, so that the deflation of these values due to correlation would tend to emphasize them during the onset of failure. The appropriate critical values in either case, then, could be obtained from the chi-square distribution with 2 degrees of freedom. We suggest using the value 10 (or 9 if the user is conservative) for the critical value of J_s.

5. A Numerical Example.

The foregoing development might appear somewhat complicated, although J_s is only slightly more complicated than (1). We maintain that J_s contains more engine history and therefore more information on which to base automated decisions. We further suggest that J_s and the related preceding formulation can be easily computed with a handheld computer or even programmed for a microcomputer. The following example will illustrate the point.

Suppose that it has been determined that a certain helicopter engine is characterized by $\mu_x(t) = 15 + .00625t$, $\mu_y(t) = 6 + .003t$, $\sigma_x^2 = 11.1$, $\sigma_y^2 = 2.75$, and t is engine operation time in hours. Suppose further that the engine Ferrogram measurements at 600, 650, and 700 hours are $(\bar{A}_L, \bar{A}_S) = (24.8, 6.1)$ (24.1,8.6), and (25.7, 12.7). First we note that $\mu_x(600) = 18.75$ and $\mu_y(600) = 7.8$. Then

$$J_s = \left(\frac{24.1 - 18.75}{3.33}\right)^2 + \left(\frac{8.6 - 7.8}{1.66}\right)^2 = 4.35$$

The other values of J_s and the values of I_s are calculated similarly and are given in the table below. Notice that while the successive values of I_s decrease, the third value of J_s exceeds the critical value, which is a signal of impending failure.

t	J_s	I_s
600	4.35	578
650	2.43	507
700	11.28	499

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